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THE MTL TORSIONAL SPLIT-HOPKINSON BAR

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MATERIALS DYNAMICS BRANCH

May 1990

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ABSTRACT

A Stored Torque Split-Torsional Hopkinson bar (THBar) was developed (based on the principle of the one located at Brown University) and constructed at the U.S. Army Material Technology Laboratory (MTL). This report provides a detailed description of the THBar and its shear, axial and bending characteristics, and use of it to generate high strain rate shear stress-strain data of annealed OFHC copper (99.99% copper). With the present clamp of the THBar, shear stress-strain data can be generated for strain rates from 200 to 1300 s^{-1}. At the highest strain rate, a specimen can be deformed in shear to a maximum strain of 85% with the shear pulse of 655 μs. Three tests have been conducted for copper at strain rates of 400, 800, and 1200 s^{-1}. The shear stress-strain curves that have been generated at these three strain rates show a strain rate sensitivity for strains less than 35%; stress increases with strain rate for a constant strain. At higher strain rates and higher strains (greater than 35% strains), shear stress saturates to a constant value independent of the strain rate. High strain rate, shear stress-strain data correlate favorably with the trend found in the quasi-static rate data from a servohydraulic test machine.

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INTRODUCTION

When numerically simulating an event such as the penetration of an armor, where material deforms at a high strain rate and temperature, results will significantly depend upon the choice and the validity of the material constitutive model that is used in the simulation. To develop new models, evaluate existing models, and to obtain model parameter constants, it is necessary to obtain experimental stress-strain data as high deformation rates.

One method of obtaining experimental high strain rate (100 to 10^4 s^{-1}), stress-strain data is by using the split Hopkinson (also known as Kolsky bar) bar technique. Split-Hopkinson bar configuration consists of two elastic bars between which the specimen is held. In this test system, a stress pulse is applied to one bar (input bar) in the direction of the other bar (output bar) by an external mean; for example, by propelling a striker bar at the input bar or releasing a stored torque in the input bar. Part of the stress pulse will travel to the output bar (through the specimen) while the remainder will reflect back into the input bar. By measuring the elastic stress waves in the input (reflected) and output (transmitted) bars, Kolsky showed that it is possible to determine the stress-strain response of the sandwiched specimen.[1] It has been demonstrated that this technique can be used to obtain stress-strain response under compressive,[2,3,4] tensile,[5,6,7] or torsional[8,9] conditions.

Though the high strain rate behavior can be obtained by either compression or tension, there are many advantages to obtaining the stress-strain behavior by the torsional (shear mode) method. For example, when testing for large strains, the strains that can be achieved by tension is limited by necking, and compression is limited by barreling of the specimen. In addition, errors arising from dispersion of longitudinal stress wave on its travel along the elastic bars in a compression or tension test are not present in a torsion test; there is no wave dispersion in shear wave transmission. Although it is assumed that the stress conditions are uniaxial in a compression or tension test, at high rates, due to radial inertia (radial stress) that is opposing the Poisson's expansion associated with uniaxial stress, stress conditions may not be fully uniaxial. In a compression test, at high strains and/or strain rates, this inertia effect may get accentuated by the radial friction at the specimen and bar interface, even with the presence of lubrication. However, in spite of these disadvantages and limitations, the compression test has the advantage of requiring a simpler and cheaper specimen compared to the torsion or tension test.

Shear also is the main form of deformation that is present in high rate deformation events such as penetration of an armor. Therefore, to accurately predict material behavior in these types of situations, material constitutive models should be developed from shear data at

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2. LINDHOLM, U. S. *Some Experiments with the Split Hopkinson Pressure Bar*. J. Mech. Phys. Solids, v. 12, 1964, p. 317.
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4. FOLLANSBEE, P. S. *The Hopkinson Bar, High Strain Rate Compression Testing, in High Strain Rate Testing, Mechanical Testing*. Metal Hand Book, American Society for Metals, v. 8, p. 198.
5. LINDHOLM, U. S., and YEAKLEY, L. M. *High Strain Rate Testing: Tension and Compression*. Exp. Mech., v. 8, 1968, p. 1.
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high strain rate and temperature. In addition, test results converted to shear from tension or compression data by using a criterion such as von Mises equivalent stress-strain is not valid at large strains above approximately 20%.[*,10] Shear tests can be conducted using a punch or double-notch type shear tests using a compression bar.[11] In this case, although high strain rates in the order of 10^4 s^{-1} could be achieved, disadvantages with compression bar such as geometric wave dispersion associated with longitudinal wave transmission, as well as non-uniform deformation in the specimen gage section will be present. However, a torsion test eliminates most of the above disadvantages. It is noted that rate change tests, also known as jump tests, (change of state keeping state variables representing the structure constant) that are required to develop and evaluate modern physically (dislocation dynamics) based high rate and temperature state variable constitutive models can be easily conducted using the torsional method. In a torsion test, shear stress pulse could be generated and released by explosives. This method of torsion testing could generate, in addition to the torsional pulse, a bending and axial pulse, as well as ringing in the torsional pulse, thus requiring elaborate mechanical filtering methods. In addition, an explosive capability has to be set up in the laboratory. In contrast, a torsional pulse that is generated and released by mechanical means (with mechanically releasing a clamp that would hold a stored torque that is generated by twisting the input bar) will not have the above complications, but will have higher rise-time and lower maximum achievable strain rate.

To facilitate the development and evaluation of constitutive models that would better predict shear behavior at high strain rate and temperature, and to make measurements such as strain and temperature in shear bands while they are being generated, a Stored Torque Torsional Hopkinson Bar (THBar) was developed at the U.S. Army Materials Technology Laboratory (MTL). This report presents the information and characteristics of the Torsional Hopkinson bar that was developed at MTL. Some preliminary torsional stress-strain data, at high strain rate and room temperature, for annealed OFHC copper (99.99% copper) from this test instrument is included in this report. High/low temperature and jump test capability are being added to the THBar.

DESCRIPTION OF THE APPARATUS

The design principal of our THBar is similar to that of the machine located at Brown University.[9] Here, the THBar consists of two elastic bars, a clamp with a sudden releasing mechanism, and a loading arrangement to twist one of the bars. Each end of the specimen is attached to one end of each bar so that the specimen is held between them. The clamp is used to hold the bar from rotating, while a twist is applied by the loading mechanism at the other end of the input bar. The release of the torque, that is stored between the loading end of the input bar and the clamp, by sudden release of the clamp will propagate a shear stress pulse along the bar toward the specimen, thus loading it in shear at high rate.

* WEERASOORIYA, T. Unpublished Research, 1989.

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Figure 1 shows a photograph of the THBar apparatus, and a schematic diagram of the THBar is shown in Figure 2. The THBar consists of two 25.4 mm diameter 7075-T6 aluminum bars, input and output bars, 2438 mm in length. These two bars are mounted on top of a square box beam, using oilite bronze bearings. The bearing stands are designed in such a way that the bearings have the freedom to move in any direction; i.e., translate along and rotate about three mutually perpendicular axes of which one axis is lying along the axis of the bearing. Once the bearings are aligned, they are locked in that position. Alignment of the bearings is performed with the help of a helium-neon laser and a steel bar, 25.4 mm in diameter and 75 mm in length, which has the two end faces precisely machined perpendicular to the axis of the bar; a mirror is mounted on one end, and a cross (two lines that are perpendicular to each other and passing through the center), are scribed at the other end of the alignment bar.

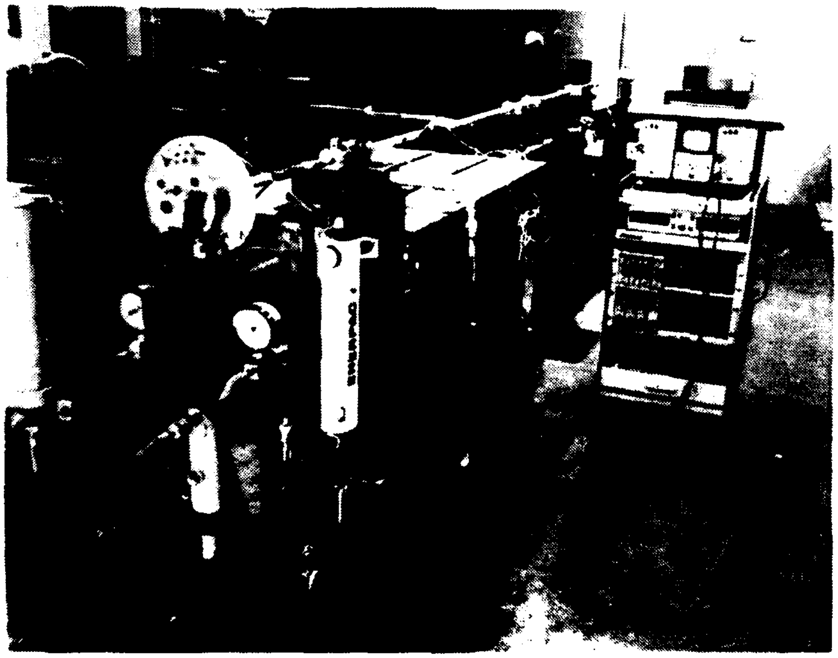


Figure 1. The Torsional Split-Hopkinson Bar Apparatus.

At one end of each aluminum bar, a hexagonal slot is machined to enable the attachment of a hexagonal-end specimen. Specimens are attached to the bar with 12 slotted screws, two on each face of the hexagon (Figure 3). Specimen geometry is discussed in a later section. When flat-end specimens are tested, these bars are replaced with two flat-end bars. In this case, using an epoxy, the specimen is glued to these flat ends of the bars.

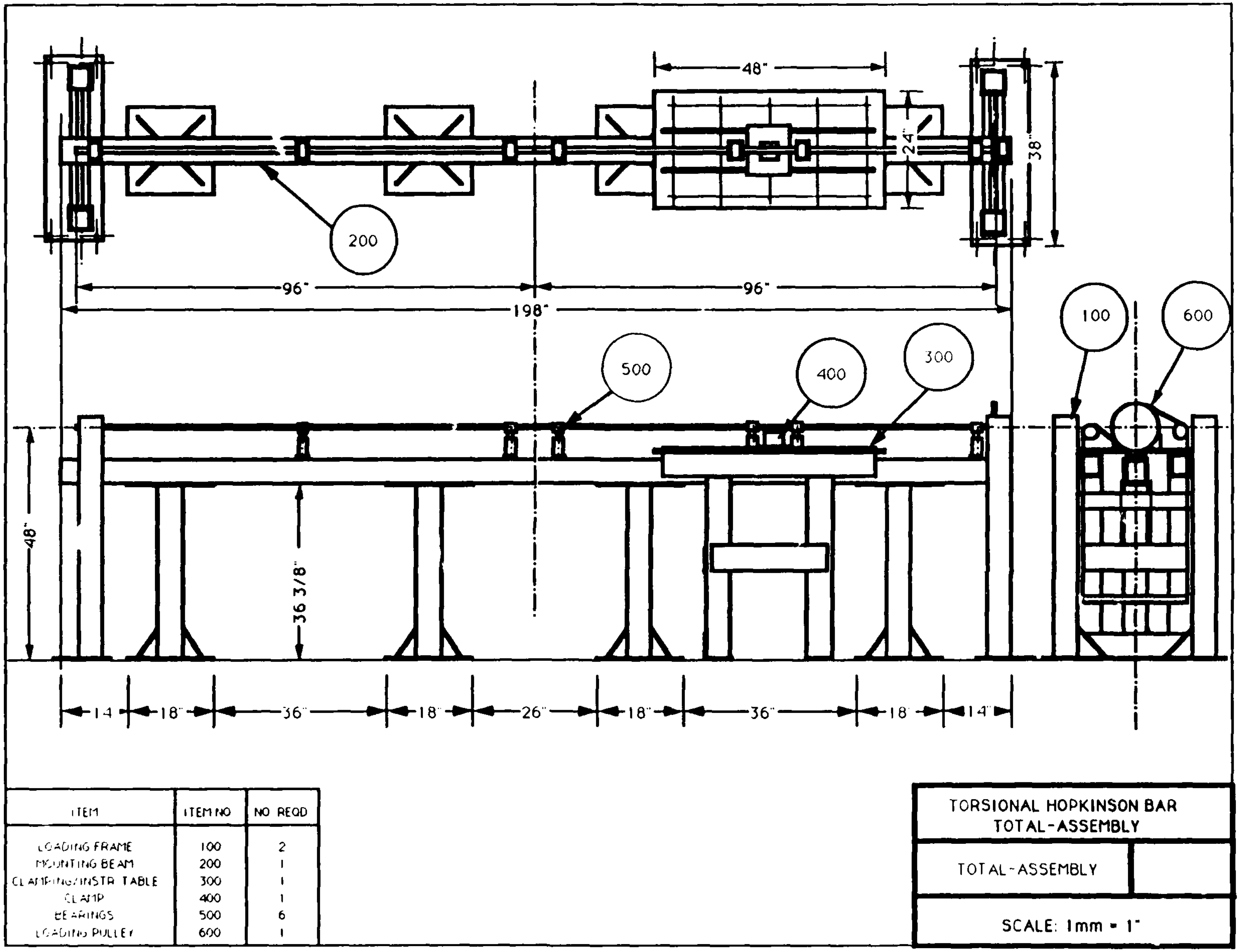


Figure 2. Schematic of the complete Torsional Hopkinson Bar Assembly.

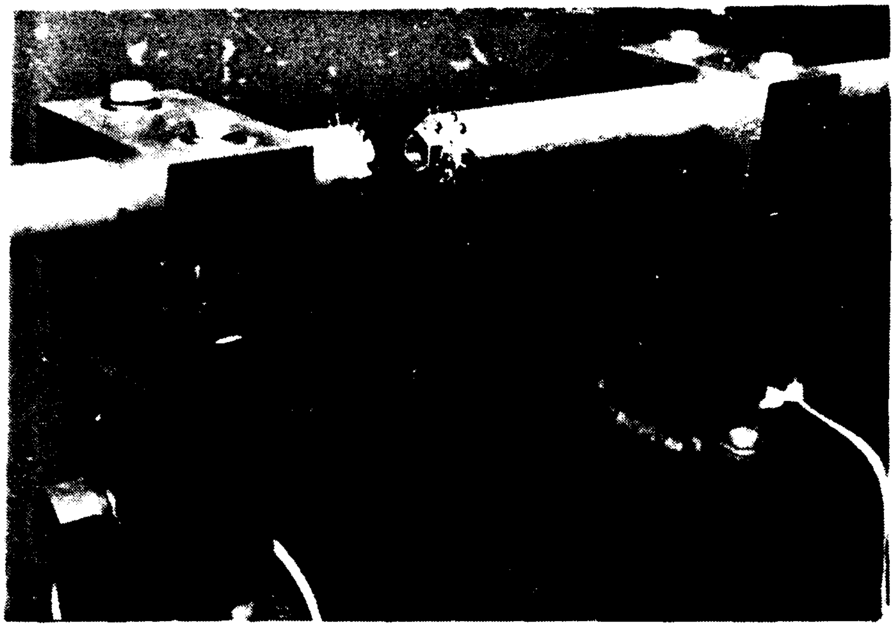


Figure 3. Specimen-ends of the bars. In this picture, hexagonal end specimen is attached to the bars via the hexagonal slots in the bars.

Shear Pulse Generating System

Torque Generating Mechanism

A torque is applied to the opposite end from the slotted-end of the input bar, via a pulley that is attached to the bar by a friction fit. Using a hydraulic hand pump and a cylinder, the pulley is rotated to apply a twist to the input bar. The schematic and photograph of this loading arrangement is shown in Figures 4 and 1, respectively. The pulley is attached to a cross bar by cables. The cross bar is pushed down by the hydraulic cylinder, thus rotating the pulley that is attached to the end of the input bar.

Clamp

A photograph of the clamping arrangement is shown in Figure 5, and a schematic diagram of the clamp is shown in Figure 6. The clamp consists of two plates that are positioned on either side of the bar. The tops of the plates are connected by a 2024-T4 aluminum pin, 19.1 mm in diameter, with a 12.2 mm diameter notch at the center. Both clamping plates are mounted in a carriage that is free to move on ball bearings perpendicular to the bar, with pins, allowing the plates to freely rotate about these pins. While clamping, application of lateral forces that would create bending and axial pulses are avoided by allowing the free movement of the clamp relative to the bar. At both ends of the clamp, to reduce any bending waves emanating from the release of the clamp, the input bar is mounted on two additional 38 mm long oilite bronze bearings, which are located on either side of the clamp. In addition to allowing the clamping plates to rotate about the attaching pins, the pin of one plate is free to move toward the bar. Clamping is achieved by pushing this plate toward the bar at this pin by a hydraulic cylinder attached to a hand pump. Further pumping of the hydraulic oil to the cylinder will fracture the notched 2024-T4 aluminum pin at the top of the bar, suddenly releasing the clamp and, therefore, the stored torque between the clamp and the loading end.

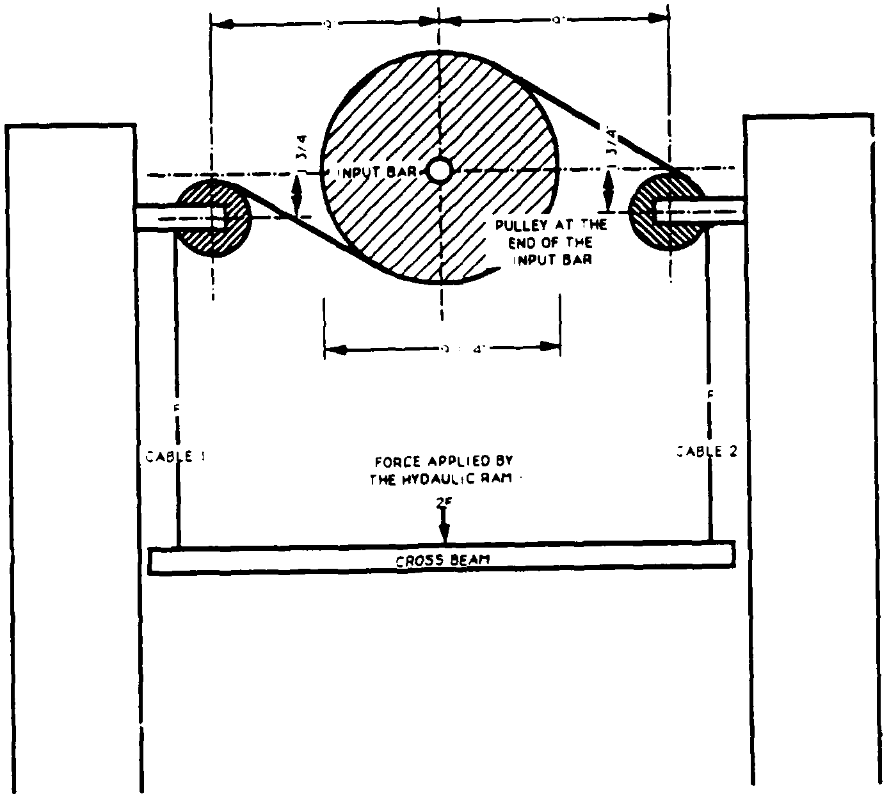


Figure 4. Schematic of the loading arrangement.

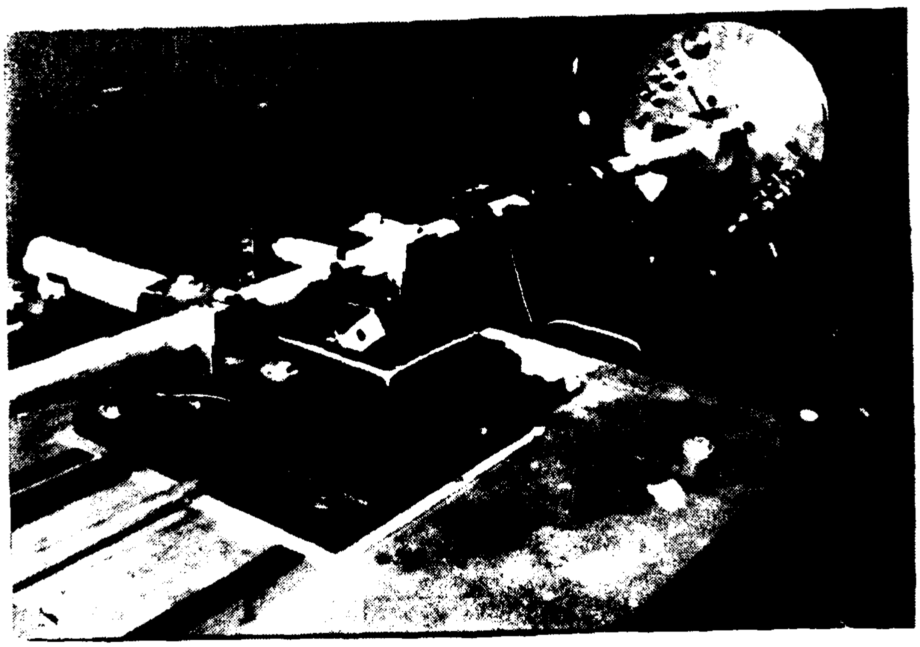


Figure 5. The clamping assembly and the loading pulley.

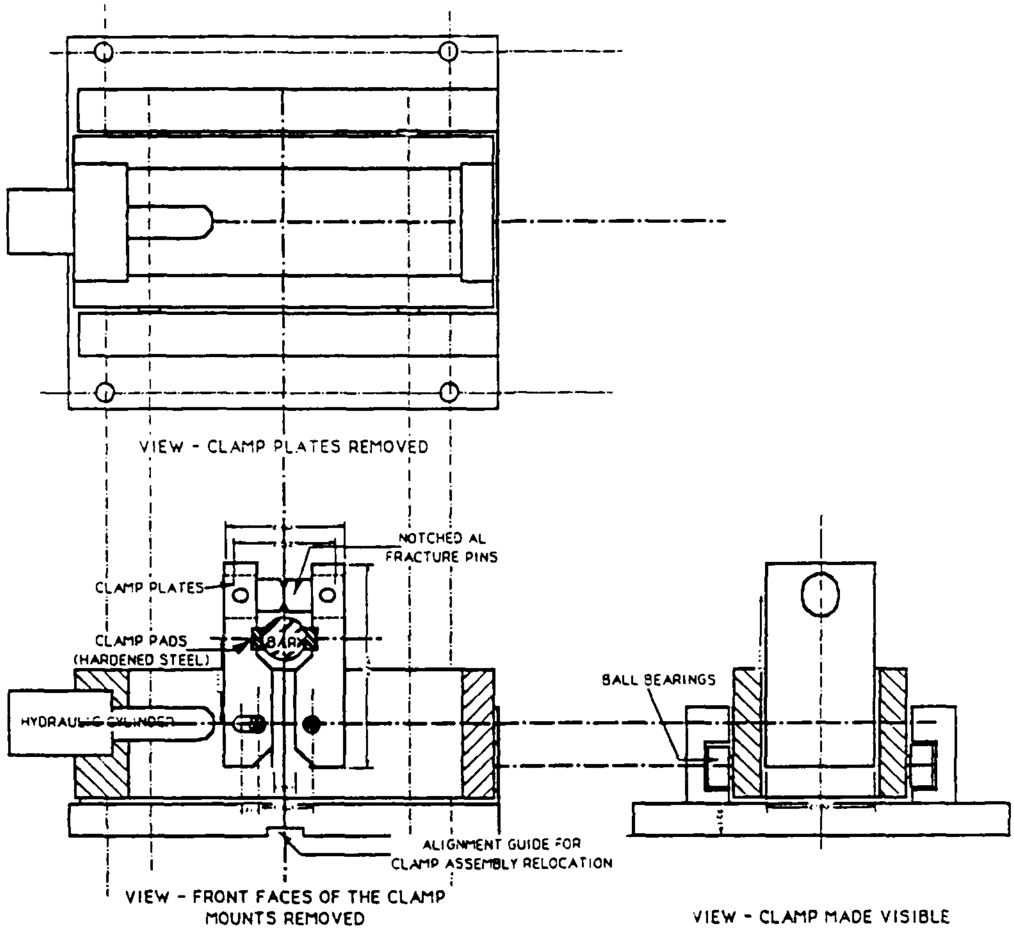


Figure 6. Schematic of the clamping assembly.

Lagrangian Diagram of the System

Langrangian of x-t diagram of the system is shown in Figure 7. The position of the shear wave front as a function of time can be inferred from this wave diagram. As seen from the diagram, at the release of the clamp, half of the torque stored between the clamp and the loading pulley will travel as a shear wave, at the shear wave speed (C_s) of aluminum, toward the specimen. Shear pulse of the same magnitude will travel at the same speed in the other direction unloading the torque that is stored at that end. This unloading pulse will reflect completely at the loading pulley (large pulley will act as a rigid boundary) and travel toward the specimen releasing the torque to zero; therefore, the total length of the shear pulse that will twist the specimen is equal to the time taken by the unloading pulse to travel toward the loading pulley and back to the clamp. By allowing the clamp to be relocated, the length of the pulse can be changed. To allow the clamp assembly to be moved and bolted easily, without drastically changing the alignment, the whole clamp assembly is mounted on a long table with guiding rails.

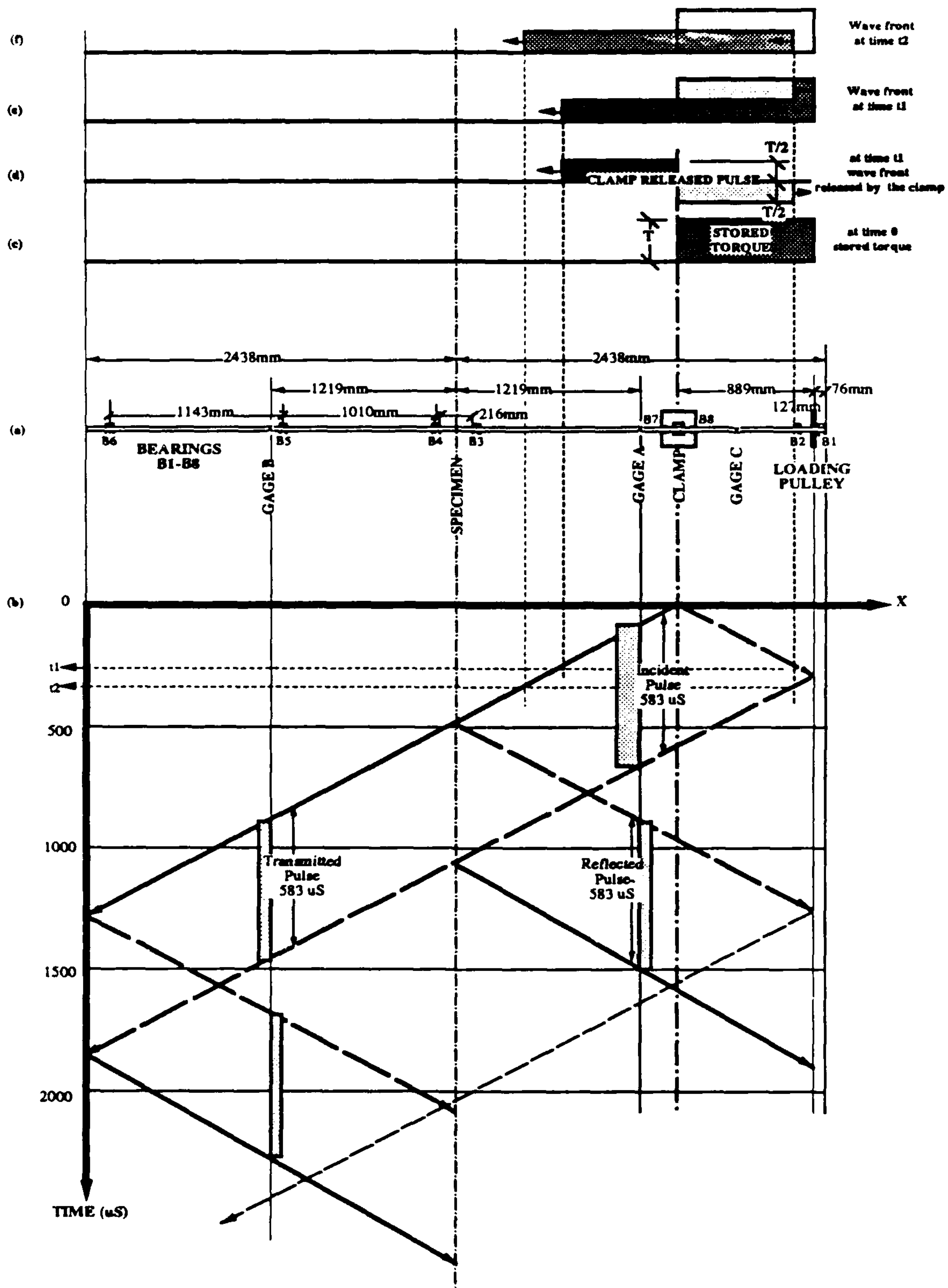


Figure 7. Lagrangian (x-t) diagram of the system.

Stress, Strain, and Strain Rate Computation

Magnitude of stress, strain, and strain rate of the specimen can be computed form the measured shear strain records of the input and output bars (Kolsky analysis method[1]). Shear strain of the specimen (γ_s) is equal to the relative rotation of the ends of the gage section of the specimen divided by its length:

$$\gamma_S = \frac{D_S \phi_1 - D_S \phi_2}{2L_S} \tag{1}$$

where ϕ_1 and ϕ_2 are angles of twist at the interface between specimen (Figure 8) and input and output bars, respectively, L_s is the gage length of the specimen, and D_s is the mean diameter of the thin wall of the specimen. The magnitude of ϕ_2 can be determined from γ_T: the transmitted shear strain at the surface of the output elastic bar:

$$\gamma_T = \frac{D}{2}\frac{\partial \phi_2}{\partial x} = \frac{D}{2C_S}\frac{\partial \phi_2}{\partial t} \tag{2}$$

where $C_S = \sqrt{G/\rho}$ is the shear velocity in the output bar, D is the diameter of the output bar, and G and ρ are shear modulus and the density of the output bar, respectively. Rearrangement yields:

$$\phi_2 = \frac{2C_S}{D}\int_0^t \gamma_T(t)dt \tag{3}$$

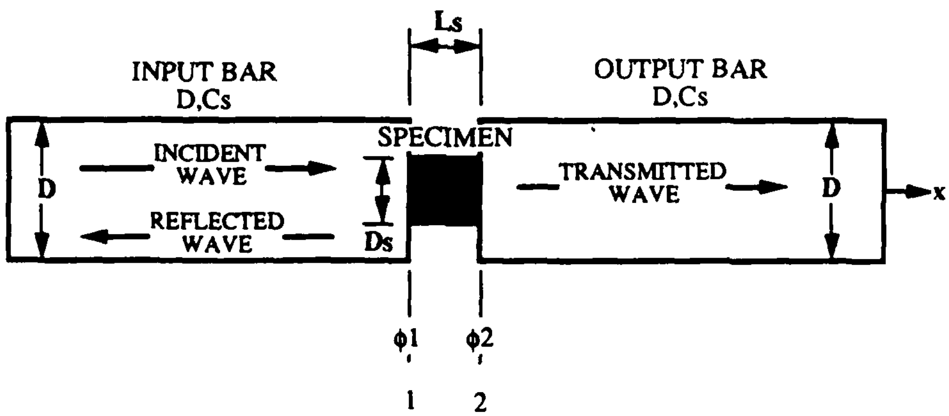


Figure 8. Schematic of the specimen bar interfaces.

The magnitude of ϕ_1 can be determined from the values of shear strains, the incident (γ_I) and reflected (γ_R) waves at the specimen/input bar interface, on the surface elastic input bar:

$$\gamma_I - \gamma_R = \frac{D}{2}\frac{\partial \phi_1}{\partial x} = \frac{D}{2C_S}\frac{\partial \phi_1}{\partial t} \tag{4}$$

and integrating

$$\phi_1 = \frac{2C_s}{D}\int_0^t [\gamma_I(t) - \gamma_R(t)]dt\ . \qquad (5)$$

By substituting the derivatives of ϕ_1 and ϕ_2 from Equations 3 and 5 in Equation 1,

$$\mathring{\gamma}_S(t) = \frac{C_s D_s}{L_s D}[\gamma_T(t) - \{\gamma_I(t) - \gamma_R(t)\}] \qquad (6)$$

By integrating the above relationship for specimen strain rate, the strain of the specimen can be determined as a function of time. At a uniform state of strain in the specimen, the transmitted torque at the output bar/specimen interface (T_2) is approximately equal to the torque at the input bar/specimen interface (T_1); i.e., the transmitted shear strain pulse is equal to the sum of the incident and reflected shear strain pulses at the specimen. Therefore, $\gamma_T \approx \gamma_I + \gamma_R$ and Equation 6 reduces to:

$$\mathring{\gamma}_S(t) = \frac{2C_s D_s}{L_s D}\gamma_R(t) \qquad (7)$$

Integration of Equation 7, strain of the specimen can be obtained:

$$\gamma_S(t) = \frac{2C_s D_s}{L_s D}\int_0^t \gamma_R(t)\, dt \qquad (8)$$

Shear stress (t_s) is given by:

$$\tau_S(t) = \frac{2T_s}{\pi D_s^2\, t_s} \qquad (9)$$

where t_s is wall thickness and T_s is average torque in the specimen: T_s is the average of T_1 and T_2, torques at the input bar interface and output bar interface of the specimen, respectively. These torques, T_1 and T_2, can be computed from the shear strains in the elastic input and output bars as follows:

$$T_1 = \frac{G\pi D^3}{16}(\gamma_I+\gamma_R) \qquad (10)$$

and

$$T_2 = \frac{G\pi D^3}{16}\gamma_T \qquad (11)$$

As discussed earlier, when the specimen is deforming uniformly; i.e., $\gamma_T \approx \gamma_I + \gamma_R$, from Equation 9 using Equations 10 and 11:

$$\tau_S(t) = \frac{GD^3}{8D_S - t_S}\gamma_T(t) \tag{12}$$

Measurement of Shear Pulses in the Bars

Shear stress pulses in the input and output bars are measured using a strain gage bridge. The strain gage bridges are attached to each bar at the mid-points (at the locations A and B in Figure 7). By locating A and B gages at the mid-points, both transmitted and reflected waves will reach the gage locations at the same instant; also, reflected and incident pulse will be separated in time in the trace captured at the A gage. In addition, another strain gage bridge (C in Figure 7) is attached between the clamp and the loading pulley; this bridge is provided to measure the magnitude of the applied (stored) torque to the bar. All the bridges consist of four strain gages. Each bridge consisting of two pairs, one pair attached diametrically opposite the other on the surface of the bar. The gages are oriented at a 45° angle to the axis of the bars; gages arranged this way will measure only shear strains by excluding both axial and bending strains.

Each bridge is powered by a separate DC power supply, an HP6218C constant voltage (50V), or current (0.2A) power supply, in which the voltage can be set with a potentiometer. Output of the bridges are directly fed into an 800 kHz Nicolet (Model 4562) digital oscilloscope. Power supply voltage output to strain gage bridges are adjusted to achieve a chosen calibration factor and is discussed in the Calibration and Data Reduction Method Section.

To measure axial and bending pulses that will be generated by the clamp, four additional strain gages are attached to the bar, 90° apart, at each A and B location. Two diametrically opposite gages are connected in series to act as the active part of a single gage bridge-amplifier setup (2 MHz bandwidth). Axial stresses are measured by this bridge configuration. The other two gages that are 180° apart are a part of a two active gage bridge-amplifier unit (2 MHz) that is set up to measure the bending stress pulses of the bar; in this case, the two active gages are located at opposite locations of the bridge.

Calibration and Data Reduction Method

Figure 9 shows typical waveforms captured by the digital oscilloscope at A and B gages. The trace from A gage contains both the incident ($v_I(t)$) and reflected ($v_R(t)$) traces separated from each other in time space. The trace from B gage represents the transmitted pulse ($v_T(t)$) through the specimen. In these traces, vertical axes represent a voltage output from the strain gage bridge that is proportional to the shear strain at the surface of the bars. For a four gage bridge, the shear strain (γ) at the surface of the bar is given by the expression:

$$\gamma = \frac{2v}{FE}\,, \tag{13}$$

where v is the output voltage of the bridge, F gage factor of the strain gages, and E is the input DC voltage of the bridge. By using Equations 13 and 7, shear strain rate of the specimen:

$$\mathring{\gamma}_S(t) = \frac{2C_S D_S}{L_S D}\frac{2v_R(t)}{FE_A} \tag{14}$$

where subscript R represents the reflected pulse and A represents the gages at A. Similarly, Equation 12 representing shear stress will become:

$$\tau_s(t) = \frac{GD^3}{8D_s^2 t_s}\frac{2v_T(t)}{FE_B} \tag{15}$$

where subscript T represents the transmitted pulse through the specimen and B represents the gages at location B. By selecting a value for $E_{A/B}$, (A or B) calibration factors (i.e., for a unit output bridge voltage) for strain rate and stress can be chosen. For chosen calibration factors, E_A and E_B can be calculated from Equations 14 and 15. With these input bridge voltages, when a known precision calibration resistor (R_c) is shunted across one gage of the bridge, the output bridge voltages ($v_{R/T}$) can be computed by the expression:

$$v_{R/T} = \frac{RE_{A/B}}{4F_{A/B}(R + R_c)} \tag{16}$$

where R is the resistance of a single gage.

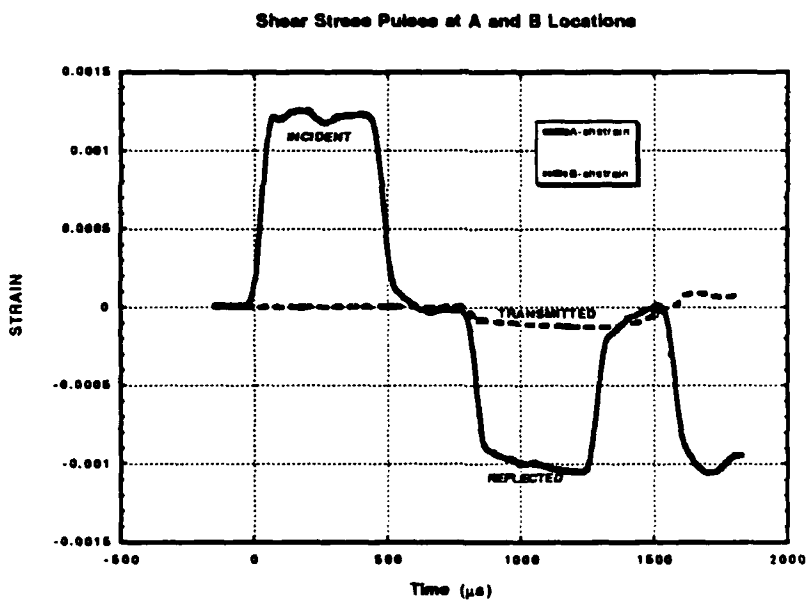


Figure 9. Shear Stress Pulses at A and B Gage Locations.

Before each test, by tuning the pot that varies the magnitude of the power supply voltage, the calibration factor is set for each bridge to output the calculated voltage for the calibration resistor.

ACQUISITION AND ANALYSIS OF STRESS PULSES

Traces of the stress pulses in both input and output bars are captured at the A gage (incident and reflected) and B gage (transmitted) using the digital oscilloscope. The oscilloscope is triggered by the trace at gage A off the incident pulse: a threshold crossing with a prescribed delay of -150 μs.

The waveforms, captured by the digital oscilloscope, are transferred to a microcomputer (AT compatible) via an RS232 serial port using a computer program written in WaveForm Basic language (see Appendix B for the listing of the program).

Shifting of the waveforms in time space, computation of strain rate (Equation 7), stress (Equation 12), strain (by numerically integrating strain rate) waveforms from captured data at A and B, and the plotting of the stress-strain curves are performed using a computer program (written in TBASIC language). The listing of the computer program is given in Appendix B.

EXPERIMENTS

In this section of the report, preliminary experiments that have been conducted with the THBar are discussed. Also, axial and bending pulses that are generated by the clamp are presented and discussed in this section of the report.

Material

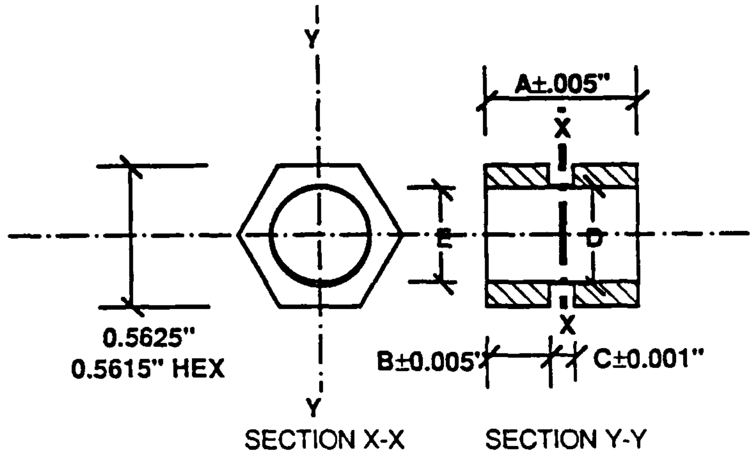
Test specimens were machined from oxygen-free-high-conductivity (OFHC) copper (99.99% copper). OFHC material was received as one inch diameter rods in the work hardened condition. Before machining the specimens, copper rods were annealed at 400°C vacuum for one hour. This annealing heat treatment produced grains of an average size of 45 μ.

Specimen Geometry

Geometry of the test specimen is shown in Figure 10. Gage section of the test specimen is a thin wall tube (0.38 mm wall thickness) of 0.254 mm gage length and of outside (D_{so}) and inside (D_{si}) diameters of 10.16 mm and 9.40 mm, respectively. A thin wall tube is sandwiched between two hexagonal flanges which are used to attach the specimen to the elastic input and output bars of the test system. Before testing the specimens, a fine line, parallel to the axis of the specimen, is scribed on the inside wall of the specimen.

The geometry of the specimen is identical to the one used at Brown University by Duffy.[9] In this short gage length specimen, an almost homogeneous state of strain is achieved after a few reflections of the loading shear stress pulse. In this specimen geometry, although the plastic zone starts at the flange-gage section interface, the plastic zone is contained until it spreads gradually through the specimen and engulfs the whole gage section.[12]

12. LEUNG, E. K. C. *An Elastic-Plastic Stress Analysis of the Specimen Used in the Torsional Kolsky Bar.* J. Appl. Mech., v. 47, 1980, p. 278.



DIM	INCHES
A	0.600
B	0.250
C	0.100
D	0.400±0.0005 DIA
E	0.370±0.0005 DIA

UNSPECIFIED TOLERANCES = ±0.005

Figure 10. Test specimen for Torsional Hopkinson Bar.

Tests

Three OFHC specimens were tested at three different strain rates, 400, 800, and 1200 s^{-1}, using the THBar. The specimens were attached to the slotted end of the bars by screws. The tests were initiated, as discussed earlier, by first clamping the bar and then twisting it by the loading assembly using the hydraulic hand pump at the loading arrangement. While clamping the bar, it was made certain that the clamp would apply its two clamping forces symmetrically opposing each other, thus cancelling any lateral force components that would apply any bending to the bar. The amount of twisting was indicated by a digital mili-voltmeter that is attached to the strain gage bridge at the location C (C gage). The clamp was released by further hand pumping of the hydraulic cylinder at the clamp. Shear stress pulses at the A and B gages were captured by the digital oscilloscope.

RESULTS AND DISCUSSION

Captured shear pulse traces, at A and B strain gage locations, for one of the tests is shown in Figure 9. As shown in the figure, this instrument produces an approximately constant incident pulse. Rise time of the incident shear wave generated by the clamp is about 45 μs.

Axial and bending strain pulses at the A gage are given with the shear strain pulse in Figure 11a for the same test. Axial and bending strain pulses that are generated by the clamp are appreciably smaller than the shear strain pulse (less than 10%).

For the same test, after transforming measured shear, axial, and bending strain pulses at the B gage to corresponding stresses through the specimen, are shown in Figure 11b. In the above conversion of axial and bending strains at B gage to stresses, the following expressions are used:

$$\sigma_a(t) = \frac{ED^2}{(D_{so}^2 - D_{si}^2)} \varepsilon_{aT}(t) \tag{17}$$

and

$$\sigma_b(t) = \frac{ED^3 D_{so}}{(D_{so}^4 - D_{si}^4)} \varepsilon_{bT}(t) \tag{18}$$

where σ_a and σ_b are axial and bending stresses at the specimen, respectively, ε_{aT} and ε_{bT} are axial and bending strains transmitted to the output bar, respectively, and E is the Young's modulus of the bar. Bending and axial stress peaks that are transmitted through the specimen are less than the static yield of the annealed OFHC copper. Moreover, the bending stress pulse travels through the specimen after the end of the shear pulse; flexural wave speed for the aluminum bar supported at locations L ($\approx$ 1300 mm) apart is approximately equal to 2.9 D/L ($\approx$ 0.06) times the shear wave speed of the bar for the zeroth overtone (free end condition is assumed). However, the axial pulse travels faster ($\approx$ 1.6 times) than the shear pulse and, therefore, it reaches the specimen earlier.

The captured stess pulses at gages A and B for the tests are transferred to the microcomputer. The reduction of these data are accomplished using the computer program in Appendix B. The resulting output from the program, stress-strain plots at the three different strain rates, 400, 800, and 1200 s^{-1} are shown in Figure 12. Computed shear strain rate, stress and strain as a function of time for the three tests are shown in Figures 13, 14, and 15, respectively.

Shear stress-strain curve of the OFHC copper at the quasi-static shear strain rate of 1×10^{-3} s^{-1} is also shown in Figure 13.* Stess-strain curves for copper at strain rates of 400, 800, and 1200 s^{-1} shows a strain rate sensitivity of this material in the range of rates that are used in the tests. At higher strain levels ($\approx$ 35%), under high strain rate conditions, stress levels seem to be independent of the strain rates. This may be due to the thermal softening of the material at higher strains and strain rates. However, no deformation shear bands were present in the gage section. High strain rate, shear stress-strain data (below 35% strain level) correlate favorably with the trend from the quasi-static rate data from a servohydraulic test machine.

It is noted from Figure 13, after a 60 μs time interval, strain rate data as a function of time for the three tests show that the strain rate remained reasonably constant during the test. This 60 μs time interval corresponds to a strain of approximately 1 to 5%, depending upon the strain rate (see Figure 15).

*WEERASOORIYA, T. *Unpublished Research*, 1989.

Strains at A-Gage Location

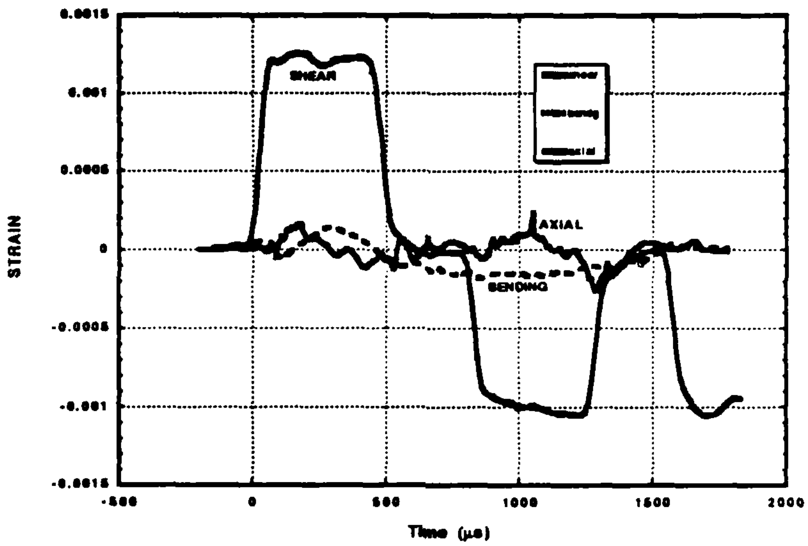


Figure 11a. Shear, Axial, and Bending Pulses at the A Gage Location.

Stresses Transmitted Through the Specimen
From B-gage Location

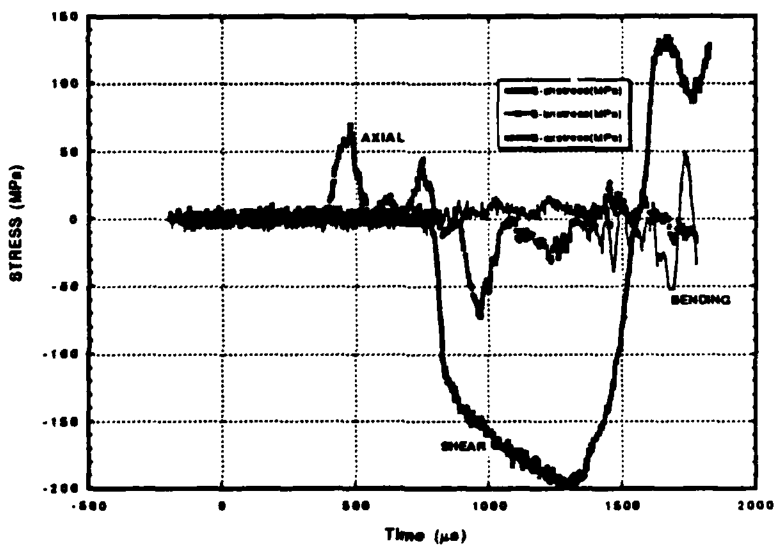


Figure 11b. Shear, Axial, and Bending stresses through the specimen from captured strain pulses at the B Gage Location.

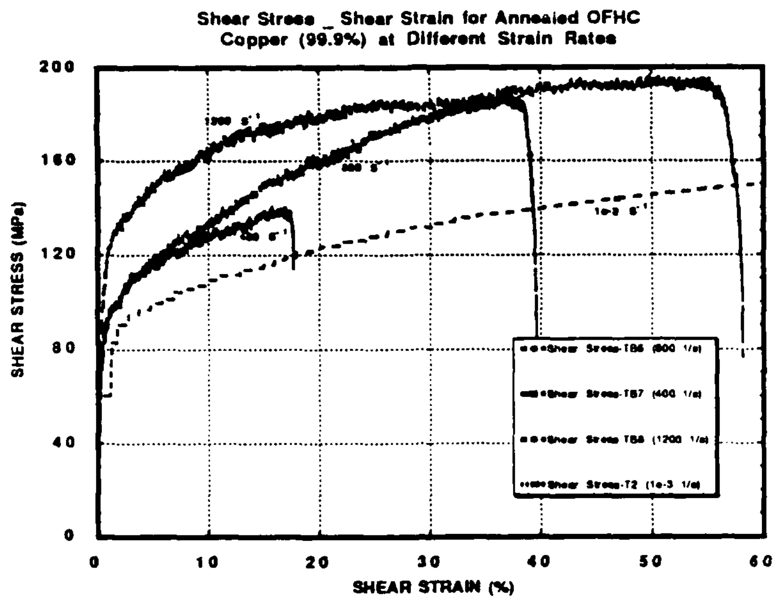


Figure 12. Shear stress-strain data at different strain rates.

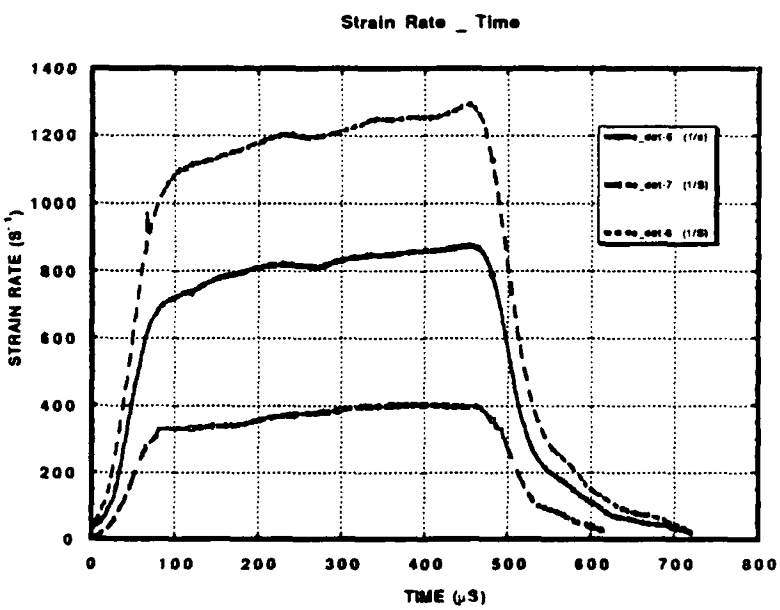


Figure 13. Strain rate as a function time for the three tests.

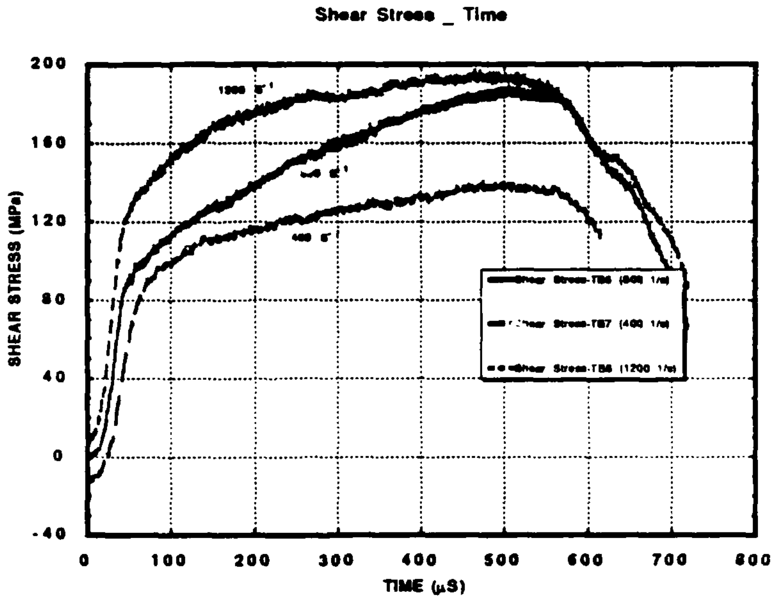


Figure 14. Stresses as a function of time for the three tests.

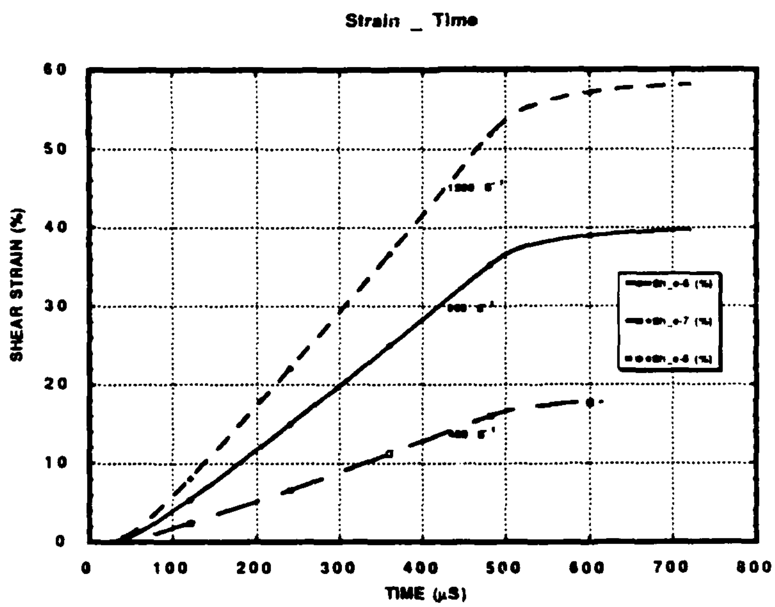


Figure 15. Strain as a function of time for the three tests.

The maximum shear strain rate that can be achieved in this THBar configuration, with the specimen of gage length of 2.54 mm and the present clamp, is 1400 s^{-1}. This maximum limit is due to the inability to apply a higher clamping force to prevent the slipping of the bar at the clamp for higher input torques; i.e., fracture load of the present aluminum fracture pin is low. In future tests, strain rates up to 2500 s^{-1} can be reached with the present specimen geometry with a new clamp that is being designed.

CONCLUSIONS

A THBar apparatus was developed and constructed at MTL. This apparatus can be used to generate constant shear stress-strain data at high strain rates, up to 1300 s^{-1}, for the development and evaluation of constitutive models that will improve the description of the shear behavior of the materials. In addition, the shear stress-strain data generated by this apparatus can be compared with the data generated by the compression or tension Hopkinson bars, using the equivalent stress-strain relationships such as von Mises. These comparisons will allow the evaluation of existing equivalent stress-strain relationships, as well as the development of better ones.

The effect from the bending and axial pulses generated by the release of the clamp is determined to be negligible. Strain rates remain reasonably constant after 60 μs (i.e., 5% strain at the highest achievable strain rate).

The apparatus is being improved to have additional capabilities. A motor drive is being developed and constructed to rotate the output bar at the far end, therefore, allowing quasi-static tests, as well as strain rate jump (sudden jump of strain rate from the quasi-static to a higher rate in the same or opposite direction) tests to be conducted. A new clamp is being developed to achieve strain rates up to 2500 s^{-1}. In addition, shear bands can be generated in some materials with this new clamp.[13]

ACKNOWLEDGMENTS

The author wishes to gratefully acknowledge the valuable input from George LaBonte of Brown University and Walter Wright of Los Alamos National Laboratory. The author highly appreciates the help given by Ron Swanson and John Green of MTL during the building of the THBar, and appreciates the encouragement given by Shun-Chin Chou, Material Dynamic Branch Chief, to complete the construction of the apparatus during a difficult period for MTL.

13. HARTLEY, K. A., DUFFY, J., and HAWLEY, R. H. *Measurement of the Temperature Profile During Shear Band Formation in Steels Deforming at High Strain Rates.* J. Mech. Phys. Solids, v. 35, no. 3, 1987, p. 283.

APPENDIX A. COMPUTER PROGRAM TO TRANSFER WAVEFORMS FROM DIGITAL OSCILLOSCOPE TO COMPUTER

```
10  TRANSFER (D@,"a2")
20  REM SELECT FIRST AND LAST POINTS BY OPERATOR-FOR A-GAGE DATA
30  SETFXP
40  SETLXP
50  AGAGE@ = CUT (D@)
60  TRANSFER (D@,"b2")
65  REM USE AGAGE WINDOW TO CUT B-GAGE DATA
70  BGAGE@ = CUT (D@)
75  REM PLOT SELECTED A-GAGE AND B-GAGE DATA
80  PLOT AGAGE@
90  PLOT BGAGE@
95  REM STORE DATA IN AN ASCII FILE
100 ASTORE AGAGE@,BGAGE@,"TBARDATA"
110 CLEAR ALL
120 CLOSE
130 END
```

APPENDIX B. DATA REDUCTION PROGRAM

```
1  !     HOPKINSON TORSIONAL BAR DATA ANALYSIS PROGRAM
2  !        WRITTEN BY TUSIT WEERASOORIYA (November 1989)
3  SET KEY ON | GOTO 100
4  PRINT "Plot STRESS_STRAIN CURVE on_",Gin$
5  SET VIEWPORT 0,130,0,100 | INPUT PROMPT "NEW PAPER AND RETURN":A$
6  Xmax = 0.6 | Xmin = 0 | Ymax = 250 | Ymin = 0
7  CLEAR | CALL Stress_strain | IF Gin$="L" THEN COPY | END
8  PRINT "Plot EPDOT_TIME on_",Gin$
10 SET VIEWPORT 0,130,0,100 | INPUT PROMPT "NEW PAPER AND RETURN":A$
11 CLEAR | CALL Epdot_t | IF Gin$="L" THEN COPY | END
12 PRINT "Plot STRAIN_TIME on_",Gin$
13 SET VIEWPORT 0,130,0,100 | INPUT PROMPT "NEW PAPER AND RETURN":A$
14 CLEAR | CALL Epsilon_t | CALL X_ticlab(1.E+06,1,"Time(uSec)")
15 CALL Y_ticlab(100,1,"Strain(%)") | IF Gin$="L" THEN COPY | END
16 PRINT "Plot STRESS_TIME on_",Gin$
17 SET VIEWPORT 0,130,0,100 | INPUT PROMPT "NEW PAPER AND RETURN":A$
18 CLEAR | CALL Sigma_t | CALL X_ticlab(1.E+06,1,"Time(uSec)")
19 CALL Y_ticlab(1,1,"Stress(MPa)") | IF Gin$="L" THEN COPY | END
20 A$ = H$ & ".MOD" | PRINT "Saving Stress_Strain curve data in ",A$,"..."
21 GOTO 4180 | END
24 INP PRO "Send graphics to the Plotter, Laserwriter, Screen (P/L/S) : ":Gin$
25 Gdevice$ = "" | IF Gin$="P" THEN Gdevice$ = "HPPLT=COM1:"
26 IF Gin$="L" THEN Gdevice$ = "IBMPRN=D:" | SET GRAPH DEVICE Gdevice$
27 SET TEXT SIZE 2,2 | SET LINE COLOR 1 | CALL Menu | END
28 IF Gin$="L" THEN COPY | END
40 CLEAR | CALL Menu
41 END
100 ! ---------------------------------------------------------------
105 INIT | CLEAR
110 Lf$ = CHR$(10) | Ashift$ = "Y" | Gin$ = "S" | Gdevice$ = ""
120 PRINT Lf$
210 OPEN #6:"LPT1","W"
220 Gin$ = "S" | INP PRO "Send graphics to the Plotter/Laser/Screen (P/L/S) : ":Gin$
225 SELECT CASE Gin$
230 CASE "P"
232      Gdevice$ = "HPPLT=COM1:"
233 CASE "L"
234      Gdevice$ = "IBMPRN=D:"
235 CASE ELSE
236      Gdevice$ = ""
237 END SELECT
238 SET GRAPH DEVICE ""
240 SET TEXT SIZE 2,2 | SET LINE COLOR 1
250 INPUT PROMPT "Enter data from file or Default file (F/D) : ":A$
260 IF A$="F" THEN
265      PRINT "Enter the Nicolet Data File Name (ex: d:\fname) "
270      INPUT PROMPT " (DO NOT ENTER EXTENSION-assumed .PRN) : ":H$
280 ELSE
290      H$ = "TB003"
300 END IF
310 He$ = H$ & ".PRN"
330 Dbar = 1.0 | Dout = 0.4 | Din = 0.37 | Lspec = 0.1 ! inches
335 Cl = 5036 | Cs = 3100 ! m/sec.
340 OPEN #7:He$,"F"
350 A$ = "K"!INP PRO "Bar and Spec. dimensions from file or keyboard-inches (F/K) : ":A$
360 IF A$="F" THEN
370      INPUT #7:Dout,Di,Lspec
380 ELSE IF A$="K" THEN
```

```
390       !INPUT PROMPT "Enter Dout, Din and Spec. length (in.): ":Dout,Din,Lspec
400  ELSE
410       GOTO 350
420  END IF
425  Dmspec = (Dout+Din)/2.0 | Th = (Dout-Din)/2.0 | Th = Th*0.0254
430  Dbar = Dbar*0.0254 | Dmspec = Dmspec*0.0254 | Lspec = Lspec*0.0254
435  Calib_a = 25000*(0.1*Dmspec/(0.385*Lspec))
436  Calib_b = 4.E+04*(0.385^2*0.015*0.0254^3/(Dmspec^2*Th))
440  Rbar = Dbar/2 | Areab = Pi/4*Dbar^2 | Areas = Pi/4*Dmspec^2
460  Delb = 48.5*0.0254 | Delc = 48.5*0.0254 | Dela = 59*0.0254
465  E = 7.1E+10 | G = 2.69E+10 ! MPa
470  Ro = 2800 | Adelt = 5.E-05
475  Cl = SQR(E/Ro) | Cs = 3100 !  CS =SQR(G/Ro) - m/sec.
477  Tshift = 2*Delb/Cs
480  Iread = 4094
490  ! READ NICOLET TWO WAVE-FORMS--------------------------------------
495  DIM Temp[2,Iread] | Temp = 0
507  ON EOF(7) GOTO 590
510  INPUT #7:T0,Temp[1,1],T0,Temp[2,1]
520  Xmin = T0/1.E+06 ! Seconds
530  Ofset1 = Temp[1,1] | Ofset2 = Temp[2,1]
545  INPUT #7:T,Temp[1,2],T,Temp[2,2]
546  Delt = (T-T0)*1.E-06 ! Seconds
560  FOR I = 3 TO Iread
570       INPUT #7:T,Temp[1,I],T,Temp[2,I]
580  NEXT I
590  CLOSE 7
595  Imax = I-1
597  DIM Wform[2,Imax],Temp0[Imax] | Wform = 0 | Temp0 = 0
600  FOR I = 1 TO Imax
610       Wform[1,I] = Temp[1,I]-Ofset1
620       Wform[2,I] = Temp[2,I]-Ofset2
630       Temp0[I] = Wform[1,I]
660  NEXT I
661  DELETE Temp
662  DIM Ep[3,Imax] | Ep = 0
670  ! -----------------------------------------
680  Xmax = T/1.E+06-Xmin | Xmin = 0 | Txmax = Xmax | Txmin = Xmin
690  Xran = Xmax-Xmin
700  CLEAR
760  CALL D_windows
780  Delt = Xran/(Imax-1) | Tmax = Txmax | Imaxp = INT(Tmax/Delt)
790  CALL P_MIN(Temp0,Ymin,Ypos) | Ymax = -Ymin ! CALL P_MAX(Temp0,Ymax,Ypos)
800  IMAGE 2D,6(4D.4D)
810  Delx = ABS(Xmax-Xmin) | Dely = ABS(Ymax-Ymin)
820  SET WINDOW Xmin-0.2*Delx,Xmax+0.1*Delx,Ymin-0.1*Dely,Ymax+0.1*Dely
830  ! DRAW TWO NICOLET WAVEFORMS IN ACTUAL TIME SPACE------------
840  SET VIEWPORT 0,65,50,100 | SET LINE COLOR 1 | SET LINE STYLE 0
850  MOVE GDU 129,2 | SET TEXT ALIGN 5,3 | SET TEXT SIZE 1.5,1.5
860  PLOT TEXT GDU H$ | SET TEXT ALIGN 0,0 | SET TEXT SIZE 2,2
870  CALL X_ticlab(1.E+06,1,"Time(uSec)") | CALL Y_ticlab(100,1,"Strain(%)")
880  AXIS Xinc,Yinc,0,0,3,3
890  FOR J = 1 TO 2
900       SET LINE COLOR J+1 | SET TEXT COLOR J+1
910       FOR I = 1 TO Imax
920            X = Xmin+(I-1)*Delt
930            Y = Wform[J,I]
940            IF I=1 THEN MOVE X,Y ELSE DRAW X,Y
950       NEXT I
960       IF J=1 THEN Title$ = " Ea,"
970       IF J=2 THEN Title$ = " Eb"
990       MOVE GDU 30+J*12,90
1000      PLOT TEXT GDU Title$
1010 NEXT J
```

```
1015  ! SHIFT REFLECTED AND TRANSMITTED WAVEFORMS AT B BY TRAVEL TIME
1017  MOVE Tshift,Ymin/2 | DRAW Tshift,Ymax/2
1020  IF Ashift$="Y" THEN
1022      PRINT "Twice the Time (uS) from A -> Specimen ";Tshift*1.E+06;
1024      INPUT PROMPT "Change the time (Y/N) ?":Ashift$
1026      IF Ashift$="Y" THEN
1028          INPUT PROMPT "Enter Time (uS) = ":Tshift | Tshift = Tshift/1.E+06
1030      ELSE
1032          SET GRAPH DEVICE Gdevice$
1034      END IF
1039      GOTO 700
1040  END IF
1042  Ishift = INT(Tshift/Delt)
1045  FOR I = Ishift TO Imax
1050      J = I-Ishift+1
1060      Ep[2,J] = Wform[1,I]
1065      Ep[3,J] = Wform[2,I]
1070  NEXT I
1072  FOR I = 1 TO Imax
1073      Ep[1,I] = Wform[1,I]
1074  NEXT I
1080  Itest = Imax-Ishift+1
1110  ! PLOT THE SHIFTED WAVEFORMS----------------------------------------
1120  SET VIEWPORT 0,65,0,50 | SET LINE COLOR 1 | SET LINE STYLE 0
1130  MOVE GDU 129,2 | SET TEXT ALIGN 5,3 | SET TEXT SIZE 1.5,1.5
1140  PLOT TEXT GDU H$ | SET TEXT ALIGN 0,0 | SET TEXT SIZE 2,2
1150  CALL X_ticlab(1.E+06,1,"Time(uSec)") | CALL Y_ticlab(100,1,"Strain(%)")
1160  AXIS  Xinc,Yinc,0,0,3,3
1170  FOR J = 1 TO 3
1180      SET LINE COLOR J+1 | SET TEXT COLOR J+1
1190      FOR I = 1 TO Itest
1200          X = Xmin+(I-1)*Delt
1210          Y = Ep[J,I]
1220          IF I=1 THEN MOVE X,Y ELSE DRAW X,Y
1230      NEXT I
1240      IF J=1 THEN Title$ = " E-ins,"
1250      IF J=2 THEN Title$ = " E-ref,"
1260      IF J=3 THEN Title$ = " E-trn"
1270      MOVE GDU 30+J*12,90 | PLOT TEXT GDU Title$
1280  NEXT J
2330  !EpIns, EpRef, EpTrn and (EpIns+EpRef)--------------------------------
2340  SET  WINDOW  Xmin-0.2*Delx,Xmax+0.1*Delx,Ymin-0.1*Dely,Ymax+0.1*Dely
2350  SET VIEWPORT 65,130,0,50 | SET LINE COLOR 1 | SET LINE STYLE 0
2360  MOVE GDU 129,2 | SET TEXT ALIGN 5,3 | SET TEXT SIZE 1.5,1.5
2370  PLOT TEXT GDU H$ | SET TEXT ALIGN 0,0 | SET TEXT SIZE 2,2
2380  CALL X_ticlab(1.E+06,1,"Time(uSec)") | CALL Y_ticlab(100,1,"Strain(%)")
2390  PLOT  AXIS Xinc,Yinc,0,0,3,3
2400  FOR J = 1 TO 4
2410      SET LINE STYLE 0 | SET LINE COLOR J+1 | SET TEXT COLOR J+1
2420      FOR I = 1 TO Itest
2430          X = Xmin+(I-1)*Delt
2440          IF J<>4 THEN Y = Ep[J,I] ELSE Y = -(Ep[1,I]+Ep[2,I])
2450          IF I<>1 THEN DRAW X,Y ELSE MOVE X,Y
2460      NEXT I
2470      IF J=1 THEN Title$ = " EpIns,"
2480      IF J=2 THEN Title$ = " EpRef,"
2490      IF J=3 THEN Title$ = " EpTrn,"
2500      IF J=4 THEN Title$ = " EpIns+EpRef"
2510      MOVE GDU 5+(J-1)*23,90 | PLOT TEXT GDU Title$
2520  NEXT J
2525  IF Gin$="L" THEN COPY else INPUT PROMPT "New paper AND Press ENTER":A$
2540  CLEAR | CALL D_windows
2550  ! Computation of Sigma, Epdot AND Epsilon-----------------------------
2555  DELETE Wform,Temp0
```

```
2560  DIM Sigma[Itest],Epdot[Itest],Epsilon[Itest],Asigma[Itest]
2570  FOR I = 1 TO Itest
2580       Asigma[I] = -Calib_b*(-(Ep[1,I]+Ep[2,I])+Ep[3,I])/2
2590       Sigma[I] = -Ep[3,I]*Calib_b        ! ((G*dbar) / ( (8*dmspec^2) *th) )
2600       Epdot[I] = -Calib_a*Ep[2,I]        ! ((2*Cs*dmspec)/(lspec*dbar))
2610  NEXT I
2620  ! Compute Epsilon by Integrating Epdot-----------------------------
2630  Epsilon[1] = (Epdot[1]+Epdot[2])*0.5*Delt
2640  FOR I = 2 TO Itest-1
2650       Epsilon[I] = Epsilon[I-1]+Delt*0.5*(Epdot[I]+Epdot[I+1])
2660  NEXT I
2670  Epsilon[Itest] = Epsilon[Itest-1]
2680  ! Epdot-Time Plot------------------------------------------------
2690  SET VIEWPORT 0,65,50,100 ! CALL Epdot_t
2700  ! Sigma-Time Plot------------------------------------------------
2710  SET VIEWPORT 0,65,50,100 ! CALL Sigma_t
2720  SET VIEWPORT 65,130,50,100 ! CALL X_ticlab(1.E+06,1,"Time(uSec)")
2730  CALL Y_ticlab(1,1,"Stress(MPa)") ! CALL Sigma_t
2740  ! Epsilon-Time Plot----------------------------------------------
2750  SET VIEWPORT 0,65,50,100 ! CALL Epsilon_t
2760  SET VIEWPORT 65,130,0,50 ! CALL X_ticlab(1.E+06,1,"Time(uSec)")
2770  CALL Y_ticlab(100,1,"Strain(%)") ! CALL Epsilon_t
2780  ! Sigma-Epsilon plot---------------------------------------------
2790  SET VIEWPORT 0,65,0,50
2800  CALL P_MIN(Sigma,Ymin,Ypos) ! CALL P_MAX(Sigma,Ymax,Ypos)
2810  CALL P_MIN(Epsilon,Xmin,Ypos) ! CALL P_MAX(Epsilon,Xmax,Ypos)
2825  CALL Stress_strain
2826  IF Gin$="L" THEN COPY ! PRINT Lf$ ! PRINT "F10 for Menu"
2827  END
2828  ! Sigma-Epsilon plot---------------------------------------------
2829  SUB Stress_strain
2830       Delx = ABS(Xmax-Xmin) ! Dely = ABS(Ymax-Ymin)
2840       SET WINDOW Xmin-0.2*Delx,Xmax+0.1*Delx,Ymin-0.2*Dely,Ymax+0.1*Dely
2850       SET LINE STYLE 0 ! SET LINE COLOR 1
2860       CALL X_ticlab(100,1,"Strain(%)") ! CALL Y_ticlab(1,1,"Stress(MPa)")
2870       AXI Xinc,Yinc,0,0,3,3 ! SET LIN STY 0 ! SET LIN COL 5 ! SET TEX COL 5
2880       FOR I = 1 TO Itest-1
2890            X = Epsilon[I] ! Y = Sigma[I]
2900            IF I<>1 THEN DRAW X,Y ELSE MOVE X,Y
2910       NEXT I
2920       ! SET LINE STYLE 1 ! SET LINE COLOR 1
2930       ! FOR I = 1 TO itest-1
2940            ! X = Epsilon[I] ! Y = Asigma[I]
2950            ! IF I<>1 THEN DRAW X,Y ELSE MOVE X,Y
2960       ! NEXT I
2970       Title$ = "Sigma(MPa)_Epsilon(%)" ! SET TEXT COLOR 1
2980       SET LINE STYLE 0 ! MOVE GDU 40,90 ! PLOT TEXT GDU Title$
2990       MOVE GDU 129,2 ! SET TEXT ALIGN 5,3 ! SET TEXT SIZE 1.5,1.5
3000       PLOT TEXT GDU H$ ! SET TEXT ALIGN 0,0 ! SET TEXT SIZE 2,2
3020  END SUB
3690  ! ------------------------------------------------------------
3700  SUB D_windows
3710       CLEAR ! SET LINE STYLE 0 ! SET LINE COLOR 2
3720       SET VIEWPORT 0,130,0,100 ! SET WINDOW 0,130,0,100
3730       MOVE 0,0 ! DRAW 0,0;130,0;130,100;0,100;0,0
3740       MOVE 65,0 ! DRAW 65,100 ! MOVE 0,50 ! DRAW 130,50
3750  END SUB
3760  ! ------------------------------------------------------------
3770  SUB X_ticlab(Xmul,Tcol,Xlabel$)
3780       SET TEXT COLOR Tcol ! SET CLIP OFF
3790       X = LOG10(Xmax) ! Xinc = INT(X) ! Xinc = 10^Xinc
3800       IF Xmax>5*Xinc THEN
3810            Xiinc = 2
3820       ELSE IF Xmax>2.5*Xinc THEN
```

```
3830            Xiinc = 1
3840        ELSE
3850            Xiinc = 0.5
3860        END IF
3870        I = 0 ! SET TEXT ALIGN 3,0
3880        DO
3890            MOVE I*Xinc,-0.05*Dely ! PLOT TEXT GDU I*Xinc*Xmul
3900            IF (I+Xiinc)*Xinc>Xmax THEN EXIT
3910            I = I+Xiinc
3920        LOOP
3930        SET TEX ALI 3,3 ! MOV Xmin+0.5*Delx,-0.1*Dely ! PLO TEX GDU Xlabel$
3940        SET TEXT ALIGN 0,0 ! SET CLIP ON
3950    END SUB
3960    ! -----------------------------------------------------------
3970    SUB Y_ticlab(Ymul,Tcol,Ylabel$)
3980        SET TEXT COLOR Tcol ! SET CLIP OFF
3990        Y = LOG10(Ymax) ! Yinc = INT(Y) ! Yinc = 10^Yinc
4000        IF Ymax>5*Yinc THEN
4010            Yiinc = 2
4020        ELSE IF Ymax>2.5*Yinc THEN
4030            Yiinc = 1
4040        ELSE
4050            Yiinc = 0.5
4060        END IF
4070        I = 0 ! SET TEXT ALIGN 5,3
4080        DO
4090            MOVE 0,I*Yinc ! PLOT TEXT GDU I*Yinc*Ymul
4100            IF (I+Yiinc)*Yinc>Ymax THEN EXIT
4110            I = I+Yiinc
4120        LOOP
4130        SET TEXT ALIGN 3,3 ! SET TEXT ANGLE 90
4140        MOVE -0.17*Delx,Ymin+0.5*Dely ! PLOT TEXT GDU Ylabel$
4150        SET TEXT ANGLE 0 ! SET TEXT ALIGN 0,0 ! SET CLIP ON
4160    END SUB
4170    ! -----------------------------------------------------------
4180    A$ = H$ & ".MOD" ! OPEN #7:A$,"F"
4190    FOR I = 1 TO Itest
4200        ! IF Epsilon[I]>0.6 OR Sigma[I]>100 THEN GOTO 4230
4210        PRINT  #7:(i-1)*delt*1e6;Epsilon[I];Sigma[I];epdot[i]
4220    NEXT I
4230    CLOSE 7
4240    END
4250    ! -----------------------------------------------------------
4260    SUB Epdot_t
4270        CALL P_MIN(Epdot,Ymin,Ypos) ! CALL P_MAX(Epdot,Ymax,Ypos)
4280        Xmax = Txmax ! Xmin = Txmin
4290        Delx = ABS(Xmax-Xmin) ! Dely = ABS(Ymax-Ymin)
4300        SET  WINDOW  Xmin-0.2*Delx,Xmax+0.1*Delx,Ymin-0.2*Dely,Ymax+0.1*Dely
4310        SET LIN COL 2 ! SET LIN STY 0 ! CAL X_ticlab(1.E+06,1,"Time(uSec)")
4320        CAL Y_ticlab(1,2,"Strain Rate(1/Sec)") ! PLO AXI Xinc,Yinc,0,0,3,3 ! SET TEX COL 2
4330        SET LINE STYLE 0 ! SET LINE COLOR 2 ! SET TEXT COLOR 2
4340        FOR I = 1 TO Itest
4350            X = Xmin+(I-1)*Delt ! Y = Epdot[I]
4360            IF I<>1 THEN DRAW X,Y ELSE MOVE X,Y
4370        NEXT I
4380        Title$ = "StrainRate_t"
4390        MOVE GDU 87,90 ! PLOT TEXT GDU Title$
4400        MOVE GDU 129,2 ! SET TEXT ALIGN 5,3 ! SET TEXT SIZE 1.5,1.5
4410        PLOT TEXT GDU H$ ! SET TEXT ALIGN 0,0 ! SET TEXT SIZE 2,2
4420    END SUB
4430    ! MENU -----------------------------------------------------------
4435    SUB Menu
4440        PRINT Lf$
4450        PRINT "F1  - Plot STRESS_STRAIN Curve"
```

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4460     PRINT "F2  - Plot EPDOT_TIME Curve"
4470     PRINT "F3  - Plot STRAIN_TIME Curve"
4480     PRINT "F4  - Plot STRESS_TIME Curve"
4490     PRINT "F5  - Write STRESS_STRAIN Data to a Disk File"
4500     PRINT "F6  - Select Graphic Device"
4505     PRINT "F7  - Print Graph to the Laserwriter"
4510     PRINT "F10 - MENU"
4530  END SUB
4540  ! -----------------------------------------------------------------
4550  SUB Sigma_t
4560     CALL P_MIN(Asigma,Yi1,Ypos) | CALL P_MAX(Asigma,Ya1,Ypos)
4570     CALL P_MIN(Sigma,Yi2,Ypos) | CALL P_MAX(Sigma,Ya2,Ypos)
4580     Ymin = MIN(Yi1,Yi2) | Ymax = MAX(Ya1,Ya2)
4590     Delx = ABS(Xmax-Xmin) | Dely = ABS(Ymax-Ymin)
4600     SET WINDOW Xmin-0.2*Delx,Xmax+0.1*Delx,Ymin-0.2*Dely,Ymax+0.1*Dely
4610     SET LINE COLOR 3 | SET LINE STYLE 0
4620     Y = LOG10(Ymax) | Yinc = INT(Y) | Yinc = 10^Yinc
4630     X = LOG10(Xmax) | Xinc = INT(X) | Xinc = 10^Xinc
4640     PLOT AXIS Xinc,Yinc,0,0,3,3 | SET LINE COLOR 3 | SET TEXT COLOR 3
4650     FOR I = 1 TO Itest
4660        X = Xmin+(I-1)*Delt | Y = Sigma[I]
4670        IF I<>1 THEN DRAW X,Y ELSE MOVE X,Y
4680     NEXT I
4690     Title$ = "Stress_Time" | SET LIN STY 0 | MOV GDU 87,85 | PLO TEX GDU Title$
4700     SET TEXT COLOR 1 | SET LINE COLOR 1
4710     FOR I = 1 TO Itest
4720        X = Xmin+(I-1)*Delt | Y = Asigma[I]
4730        IF I<>1 THEN DRAW X,Y ELSE MOVE X,Y
4740     NEXT I
4750     Title$ = "AvStress_Time" | MOVE GDU 87,80 | PLOT TEXT GDU Title$
4760     MOVE GDU 129,2 | SET TEXT ALIGN 5,3 | SET TEXT SIZE 1.5,1.5
4770     PLOT TEXT GDU H$ | SET TEXT ALIGN 0,0 | SET TEXT SIZE 2,2
4780  END SUB
4790  ! -----------------------------------------------------------------
4800  SUB Epsilon_t
4810     CALL P_MIN(Epsilon,Ymin,Ypos) | CALL P_MAX(Epsilon,Ymax,Ypos)
4820     Delx = ABS(Xmax-Xmin) | Dely = ABS(Ymax-Ymin)
4830     SET WINDOW Xmin-0.2*Delx,Xmax+0.1*Delx,Ymin-0.2*Dely,Ymax+0.1*Dely
4840     SET LINE COLOR 4 | SET LINE STYLE 0
4850     PLOT AXIS Xinc,1,0,0,3,3 | SET TEXT COLOR 4
4860     FOR I = 1 TO Itest
4870        X = Xmin+(I-1)*Delt | Y = Epsilon[I]
4880        IF I<>1 THEN DRAW X,Y ELSE MOVE X,Y
4890     NEXT I
4900     Title$ = "Strain_Time" | MOVE GDU 87,75 | PLOT TEXT GDU Title$
4910     MOVE GDU 129,2 | SET TEXT ALIGN 5,3 | SET TEXT SIZE 1.5,1.5
4920     PLOT TEXT GDU H$ | SET TEXT ALIGN 0,0 | SET TEXT SIZE 2,2
4930  END SUB
4940  ! -----------------------------------------------------------------
```

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THE MTL TORSIONAL SPLIT-HOPKINSON BAR -
Tusit Weerasooriya

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Hopkinson bar

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